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ATMOSPHERIC AND ENVIRONMENTAL RESEARCH, INC.
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Studies of the Gas Tori of Titan and Triton

William H. Smyth

and

M. L. Marconi

Atmospheric and Environmental Research, Inc.
840 Memorial Drive
Cambridge, MA 02139-3794

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I. INTRODUCTION

The general objective of this project is to advance our theoretical understanding of gas tori for the outer planet satellites and hence to enhance our ability to interpret observational data and to make available key concepts or quantitative results that are relevant to a number of other related theoretical studies. These studies include the aeronomy and photo- and ion chemistry of satellite atmospheres and their predicted gas loss rates, the evolution and distributions of gases in the larger planetary environment, and the ion loading and other impacts of these gases on the composition, structure, and properties of the planetary magnetospheres. Important objectives of this project are to explore for the satellites Titan and Triton the effects of two new mechanisms that we have very recently discovered (Smyth and Marconi 1993) to operate on gas tori in the outer planet satellite systems. These two mechanisms can dramatically alter the current picture that has been widely adopted for the structure and evolution of long-lived gas tori (i.e., lifetime long enough to achieve approximate azimuthal symmetry about the planet) and, in particular, have profound consequences on the interpretation of Voyager data for both neutral and ionized species in the circumplanetary environments of Saturn and Neptune. Due, however, to the substantially reduced budget support available for this project, the primary emphasis of the research will be focused on the Titan component, with a limited effort to be expended on the Triton component.

For the Saturn system, comparable amounts of thermal H and H_2 and a much smaller amount of nonthermal N are thought to escape Titan and form gas tori. These tori are thought to be essentially collisionless because the lifetime loss processes of these gases in the moderate Saturn magnetosphere, although slow, are sufficiently rapid to avert collisional conditions. For the atomic hydrogen torus, the perturbation of solar radiation pressure experienced by H atoms as they resonance scatter Lyman-α photons --- the first new mechanism --- was shown by Smyth and Marconi (1993) to be operative and to destroy the normally assumed cylindrical symmetry of the torus produced by the $1/r$ central potential of a planet. This new mechanism causes H atom orbits to evolve inward as their eccentricities increase, and a significant fraction of these atoms are lost from the torus (having a preferred orientation of their perigee-axes) by colliding with the planet near its dusk side before they are otherwise lost through lifetime processes. This time evolution for a typical H atom lost from Titan is shown in Figure 1. Solar radiation pressure thus provides a natural mechanism for understanding the asymmetric distribution of hydrogen about Saturn recently reported by Shemansky and Hall (1992). This new understanding will subsequently allow the current question of the consistency of this atomic hydrogen distribution with the composition and properties of the inner magnetospheric plasma and the inner icy satellite tori to be addressed more clearly. In contrast to atomic hydrogen, H_2 and N will escape Titan and form approximately azimuthally symmetric tori about Saturn (i.e., the traditionally adopted torus picture) since, for both species, solar radiation pressure is not important and the loss by lifetime processes is sufficiently long to achieve symmetry. The study of the spatial nature and the study of the physical consequences of all three of these gas tori of Titan are undertaken in this project in a straightforward three-year program summarized in Table 1.

For the Neptune system, comparable amounts of H and H_2 and N are thought to escape thermally from Triton and form gas tori. The lifetimes of these three gases in the magnetosphere of Neptune are, however, very long and are comparable to their photo-lifetimes because of the low plasma density and the small fraction of time that the tori spend in the more dense regions of the magnetosphere which executes complex motion about the planet. Because of these long lifetimes, the density of each torus will be collisional, and the neutral-neutral collision time will be shorter than all other time scales except for the typical Kepler orbit period of the atom or molecule (see Table 1 in Smyth and Marconi 1993). The collisional nature of the three gases will cause the multi-species gas torus to dynamically evolve in an inherently nonlinear manner that will depend upon the 1/r nature of the potential of the planet. This collisional evolution will cause the gas torus to expand both inwardly (leading to inward gas loss by collision with the planet's atmosphere) and outwardly (leading to volume dilution and outward gas loss by escape from the planet). This expansion mechanism, the second new mechanism noted above, is a non-linear effect that has been known for two decades in the field of solar system and ring formation but has been previously overlooked as important until now for the field of collisional gas tori about planets (Smyth and Marconi 1993). The final structure and density of the gas torus of Triton are particularly important in understanding the plasma sources recently identified in the analysis of the Voyager PLS data for the Neptune magnetosphere. This fascinating new expansion mechanism for the multi-species collisional gas torus of Triton provides a challenging dynamical evolution problem. Due to the reduced budget support available for this project, the solution of this problem to be undertaken in this project for Triton will be diminished in scope from that outlined in the original three-year plan summarized in Table 1. The Triton component will be initiated when it is clear that significant progress will have been achieved for the Titan component.

II. STUDIES FOR THE TITAN TORUS

2.1 Model Description

The model has been enhanced in several ways in the second project year. The model now supports a central planetary source and ring source in addition to the satellite source. The central source and ring source can either emit uniformly over all the surface or uniformly on the sunlit portions only. For all current sources a choice of a monoenergetic, Maxwell Boltzmann, or a sputtering initial velocity distribution is possible. Collision with the rings of Saturn are now also taken into account.

2.2 Model Calculations

We have begun to compare our model calculations for the hydrogen distribution about Saturn to the measurements presented in Shemansky and Hall (1992). In particular, the measurements depicted in Figure 10 of Shemansky and Hall have been the primary targets of our analysis thus far. In Figure 10 of their paper, Shemansky and Hall have rendered observations in Lyman-α taken by Voyager 2 during the period 1980 DOY 180 to 186. They plot average slit intensity as a function of distance of the center of the slit from Saturn in planetary radii (R_S). The projection of the slits on the observing plane is presented in their Figure 9. In Figure 2 of this report, we compare these observations with the model calculated brightness predicted for a purely Titan source of H emitted at an exospheric temperature of 186 K. In this model calculation 2000 particles were used. The match between the observation (asterisks) and the model (solid line) is reasonable at and beyond the distances where the peaks occur in the model brightness distribution. The flux of hydrogen from Titan required to produce this model intensity distribution is 4 x 10^{27} hydrogen atoms sec^{-1} which is similar to previous estimates (Ip 1996). Inside of the peaks, however, there is a large discrepancy between the observation and model brightness. This strongly suggests the existence of a source of neutral hydrogen within Titan's orbital radius of 20 R_S.

In Figure 3 we have combined the Titan source described above with a source at the orbital position of the satellite Rhea at 8.7 R_S. The hydrogen emitted from the orbit of Rhea was assumed to be Maxwellian at a temperature of 3 eV. The choice of temperature was selected as a typical energy associated with hydrogen, i.e., dissociation excess energy and bond energy are all in the range from about 2 to 5 eV. The results as represented in Figure 3 are not particularly sensitive to the precise value of temperature in this range, and so 3 eV represents a reasonable typical choice. The solid line is the smoothed model H brightness summed along the slit as described above for the observation while the asterisks are the same data that were plotted in Figure 2. The observed brightness within the two dotted lines is highly uncertain and may be ignored. Overall the sum of a Titan and Rhea source appears to be a good fit to the observation especially taking into account that the structure in the data is questionable (Hall 1996) and a monotonic best fit line through the data points maybe a better base of comparison for the observations.

The production rate of hydrogen required in Figure 3 was 3 x 10^{27} H atoms sec^{-1} for the Titan source and 1.8 x 10^{28} H atoms sec^{-1} for the source at Rhea. We do not suggest that there is some source exclusively located at Rhea's orbit which is responsible for all of inner magnetospheric hydrogen. Rather since the basic morphology of the hydrogen brightness distribution as depicted in

Figure 3 is similar for any source of ~3 eV hydrogen located at any orbital radius within the orbit of Rhea, a qualitatively similar result would be obtained by using a distribution of sources at different radii as the actual system would require. Thus the source rate of the 1.8×10^{28} H atoms sec^{-1} may be regarded as an estimate of the total rate for the non-titanogenic hydrogen. With this assumption, it is also interesting to note that if the total number of H atoms from the Rhea source between $\pm$ 5 R_S of Saturn is divided into the total number of H atoms from the Rhea source, the result is ~ 3. If one assumes two H atoms for each H_20 generated, then the production rate of H_2O necessary to produce the H atoms seen within 5 R_S may be estimated as $1/3 \times 1/2 \times 1.8 \times 10^{28}$ molecules $sec^{-1} = 3 \times 10^{27}$ molecules sec^{-1} which is similar to the estimate of Shemansky and Hall (1992). Due to the great difference in the models, however, the close agreement is probably fortuitous.

It is notable that a substantial supply of hydrogen from Saturn does not appear to be needed. In fact Figure 8 of Shemansky and Hall together with other model runs suggest that either the hydrogen from Saturn is strongly localized near Saturn or the Saturn source is weak, so as to contribute much less to the hydrogen brightness than the Rhea-like sources discussed above.

The fit achieved in Figure 3 with a Titan and Rhea source is probably not unique. By changing the velocity distribution and using a distributed source it is likely that equally good or even better fits can be obtained. The common characteristics of the models that are adequate fits will provide the constraints on the system. The utilization of the image of the H brightness distribution displayed in Figure 1 of Shemansky and Hall may provide further constraints. Consequently, we will be comparing different source distributions with the one-dimensional and two-dimensional observations of Shemansky and Hall in order to obtain robust constraints on the nature of the source and the source strength of hydrogen. These activities will be completed in the third year, and study of this Neptune/Triton system initiated if there is time left.

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Table 1

GAS TORI: THREE-YEAR PLAN OF STUDY

Subject	First Year	Second Year	Third Year
1. Titan Gas Tori			
H Torus	Complete model development; compute the density distribution and Lyman-α brightness distribution in the Saturn environment.	Investigate the Voyager UVS Lyman-α observations; evaluate the relative importance of the Titan source and an asymmetric Saturn hydrogen source.	Investigate the consistency of the atomic hydrogen distribution with the composition and properties of the magnetospheric plasma and the inner icy satellite tori.
H_2 and N Tori	-----	Set up the gas tori models for H_2 and N.	Calculate the density of the H_2 and N tori and their ion sources for the planetary magnetosphere.
2. Triton Gas Tori			
H, H_2 and N Tori	Develop a general model for the dynamical evolution of a collisional multi-species gas torus.	Complete development; explore the dynamical evolution for the restricted case of a single-species gas torus for H, H_2 and N individually.	Explore the dynamical evolution for a multi-species gas torus for H, H_2, and N.

FIGURE CAPTIONS

Figure 1. **Time Evolution of a Hydrogen Atom Lost from Titan.** The projection on the satellite plane of the initial orbit of a hydrogen atom lost from Titan is labeled by 1. This typical orbit has a semimajor axis of 22 Saturn radii, an eccentricity of 0.14, an inclination angle of 23° relative to the satellite plane, a right ascension of the ascending node of - 90°, and an argument of perigee of 242°. The time evolution of the hydrogen atom orbit is illustrated by its projected orbit on the satellite plane labeled by 2, 3 and 4 and corresponds, respectively, to times of 3×10^7 s, 5×10^7 s, and 7×10^7 s. The planet is indicated by the circle at the intersection of the two axes in the satellite plane, and the direction of the sun is to the right as indicated by the star symbol. The hydrogen atom collides with the planet near its dusk side in about 10^8 s.

Figure 2. **Comparison Between the Observations and a Titan Only Source.** The asterisks represent the Lyman-α brightness (Rayleighs) of hydrogen as measured by the Voyager 2 spacecraft taken in 1980 between DOY 180 and DOY 186 and presented in Figure 10 of Shemansky and Hall (1992). The solid line represents the model hydrogen brightness produced by Titan only source. The hydrogen was assumed Maxwell-Boltzmann distributed at 186 K, and 2000 particles were used. The dotted lines represent a region where the comparison should be ignored since the error in the observations is very large.

Figure 3. **Comparison Between the Observations and a Combined Hydrogen Source at Titan and at Rhea's Orbit.** Asterisks are the same observations as in Figure 3. The solid line is a combined Titan source with strength 3×10^{27} atoms sec^{-1} and a source at Rhea's orbit with a strength 1.8×10^{28} atoms sec^{-1}. The hydrogen from Titan is assumed as above, while the hydrogen from Rhea's location is taken to be Maxwell-Boltzmann with a temperature of 40,000 K.

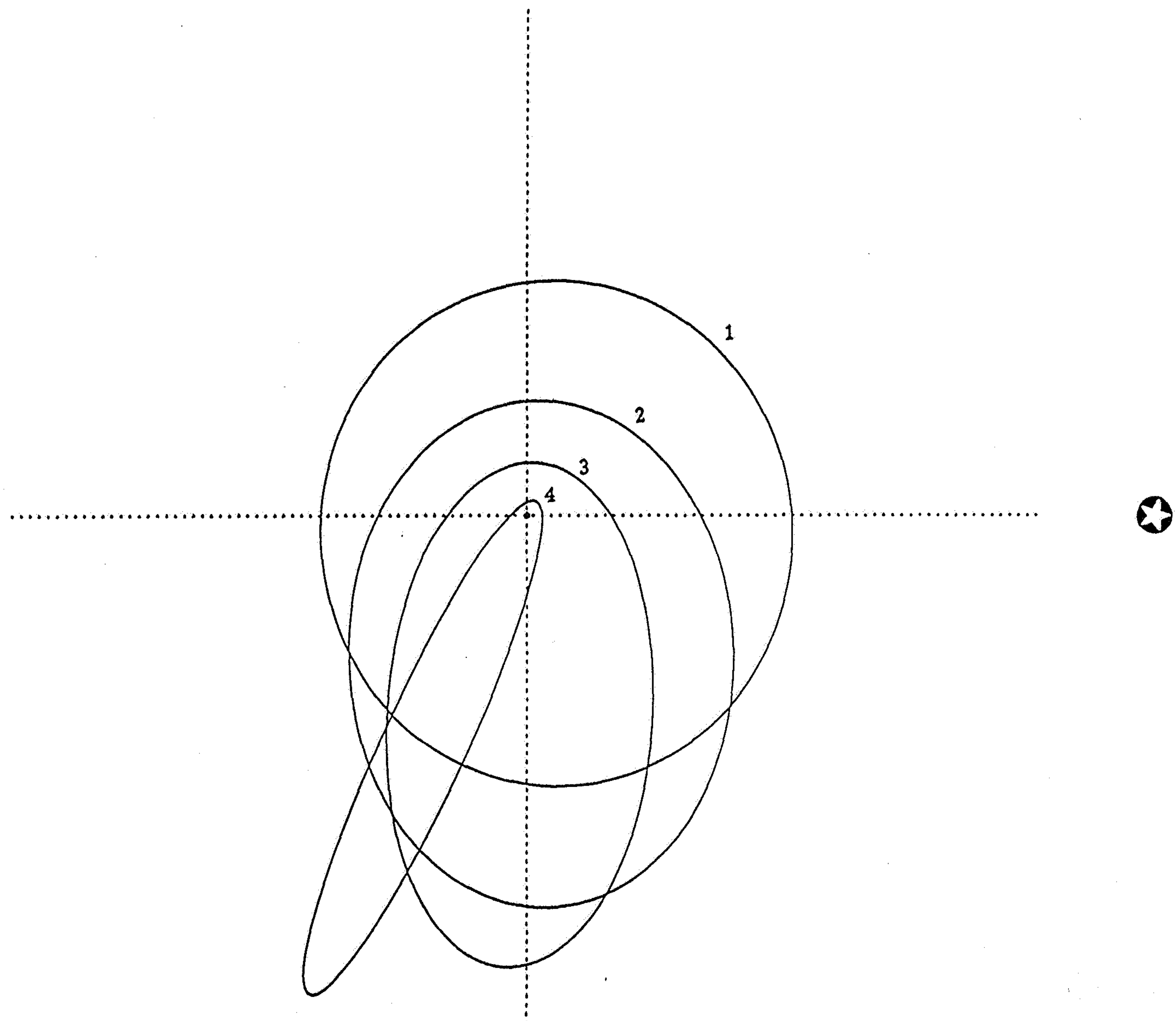
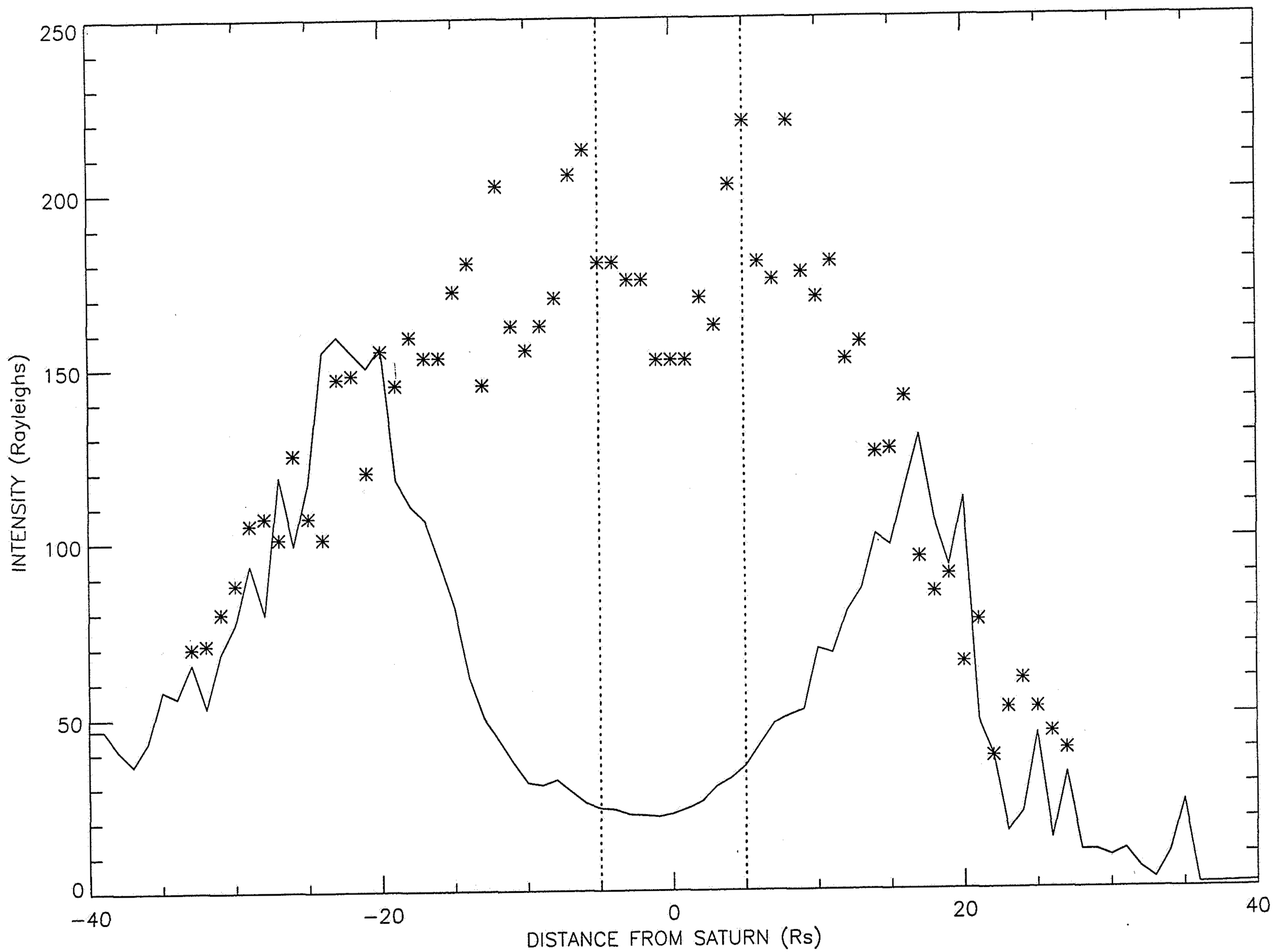


Figure 1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200
150
100
50
0
INTENSITY (Rayleighs)
-40
-20
0
20
40
DISTANCE FROM SATURN (Rs)

Figure 2

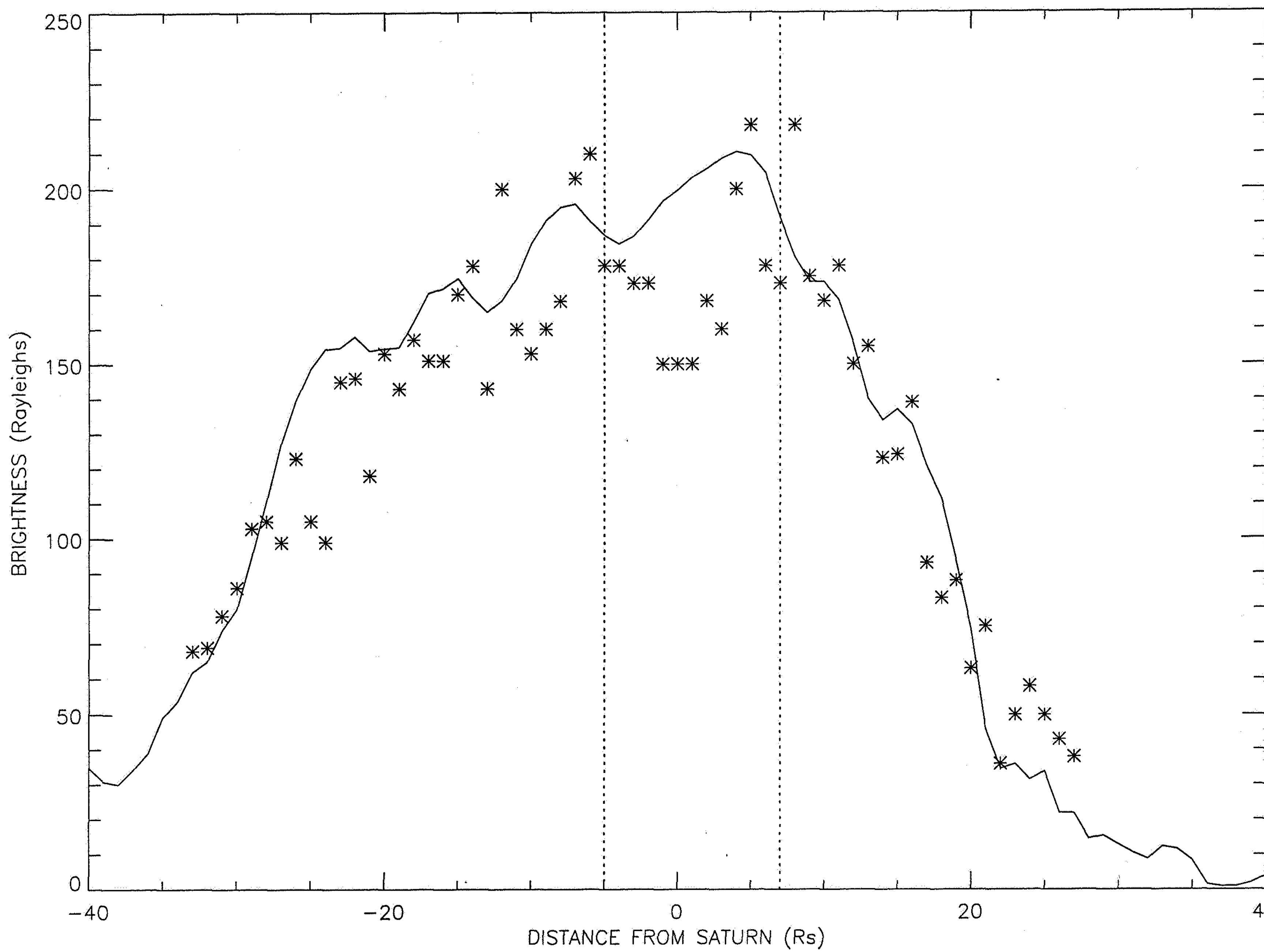
250
200
150
100
50
0
BRIGHTNESS (Rayleighs)
−40
−20
0
20
40
DISTANCE FROM SATURN (Rs)

Figure 3

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Progress in the comparison of our model of the circumplanetary distribution of atomic hydrogen in the Saturn system with observations presented in Shemansky and Hall (1992) is discussed. It is shown that a Titan source cannot by itself account for the observed distribution. A combination of a source at Titan with strength 3 x 10^{27} H atoms sec^{-1} and a source at the orbit of Rhea or perhaps a distributed source inside of Rhea's orbit with a strength of 1.8 x 10^{28} H atoms sec^{-1} is in good agreement with the data presented in Figure 10 of Shemansky and Hall.

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